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METHODS OF INTERPRETING GROUND STRESS BASED ON UNDERGROUND STRESS MEASUREMENTS AND NUMERICAL MODELLING

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ABSTRACT: This paper presents several new methods to help interpretation and understanding of ground stress. The methods are based on data from 239 stress measurements conducted in the virgin ground in NSW and Queensland mines and computational models simulating large scale faulted ground behaviour**.**

The underground stress regime plays an important role in mining profitability and safety however, understanding of the stress tensor is often difficult due to its mathematical complexities and non-intuitive behaviour. The aim of this study is to explain stress distribution in faulted ground, its origin and propose several methods of stress interpretation.

Major findings presented in this study include: increase of maximum horizontal stress with depth based on underground measurements and numerical simulation of faulted ground, affect of faults on ground stress, normalisation technique that allows comparison of lateral stress magnitudes in rock of different stiffness, 'Strain Tectonic Factor' concept and its value in understanding stress components and its affect on rock strength.

INTRODUCTION

To date, SCT has conducted some 434 successful underground stress measurements in Australian and overseas mines. From these, 353 measurements were conducted in Australian mines and 239 tests measured pre-mining stress conditions. All stress measurements used the overcoring method of three-dimensional stress determination predominantly using the ANZI stress cell (Mills, 1997.)

The large sample of test data presented here provides an ideal opportunity to assess the *in situ* stress behaviour in faulted strata. This paper includes summary of the stress measurement data, methods to interpret these measurements and attempts to explain stress distribution within the tectonically strained faulted ground. The underground stress levels are sensitive to parameters such as rock stiffness, geological discontinuities, pore water pressure and gas desorption. These parameters need to be considered as they can significantly influence the measured stress in different locations and rock types. Some of these parameters are addressed here to provide understanding how they influence stress flow in rock and what methods can be used for the correct data interpretation.

To explain one of the possible mechanisms responsible for high lateral stress underground, tectonic movement of faulted strata was modelled using Universal Distinct Element Code (UDEC), (Itasca, 1999) and Fast Lagrangian Analysis of Continua (FLAC), (Itasca, 1993). The range of results obtained from the models is compared to the measured stress field underground.

INFLUENCE OF STRATA STIFFNESS ON STRESS

The vertical stress is driven by the gravitational load of the overburden strata. Horizontally bedded strata of different stiffness compress fully until they are able to carry the full overburden weight. The vertical stress will therefore be the same in all types of rock or coal strata. On the other hand, a large portion of the regional lateral compressive stress is usually of the tectonic origin caused by the movement of the Earth's crust. In the horizontally bedded strata, stiffer rock would attract more of a tectonic lateral stress than strata of a low stiffness. The principle of stress distribution in materials of variable stiffness is illustrated in Figure 1.

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In many cases the maximum compressive stress in rock strata is expected to be horizontal and oriented in directions typical to the region. Experience indicates that rock stiffness and therefore the measured lateral stress magnitudes vary considerably in stratified roofs. To compare stress levels between two sites, stresses in rock of the same stiffness must be known. It would be impractical to look for rocks of similar properties during the measurements and therefore a 'normalising' (scaling) technique was developed to calculate stress in rock of any stiffness.

NORMALISING STRESS TENSOR

Three principal stresses σ_1, σ_2, σ_3 describe the three-dimensional stress tensor oriented in the unique direction at which all shear stresses are equal to zero (Herget, 1988). A change in magnitude of any principal stress would influence other principal stresses via the Poisson's Ratio (ν). The vertical stress in continuous bedded strata would be the same in all types of rock while the lateral stress would vary with rock stiffness. When scaling the three-dimensional stress tensor to a rock of different stiffness, the vertical stress must remain the same while the lateral stress components would change.

The gravity driven vertical stress (σ_v) induces a lateral compressive stress in strata equal to $\sigma_v\ \nu/(1-\nu)$ (Goodman, 1989). Assuming that the *in situ* Poisson's Ratio (ν) is similar in most rock types ranging 0.2-0.3 in value, the gravity induced lateral stress within the adjacent rock beds will range from 0.25 to 0.42 times the vertical stress. However, the *in situ* stress measurements indicate that the lateral stress magnitudes are in most cases much larger than the gravity induced lateral stress with a typical range from 1.5 to 4 times the vertical stress depending on location and the overburden depth. In virgin ground the 'excess' lateral stress is usually of a tectonic origin (Herget, 1988) and proportional to the rock stiffness (see Figure 1). The tectonic stress component determined from measurements will be dependent on large scale tectonic loading, geological structure, lithology and hydrology.

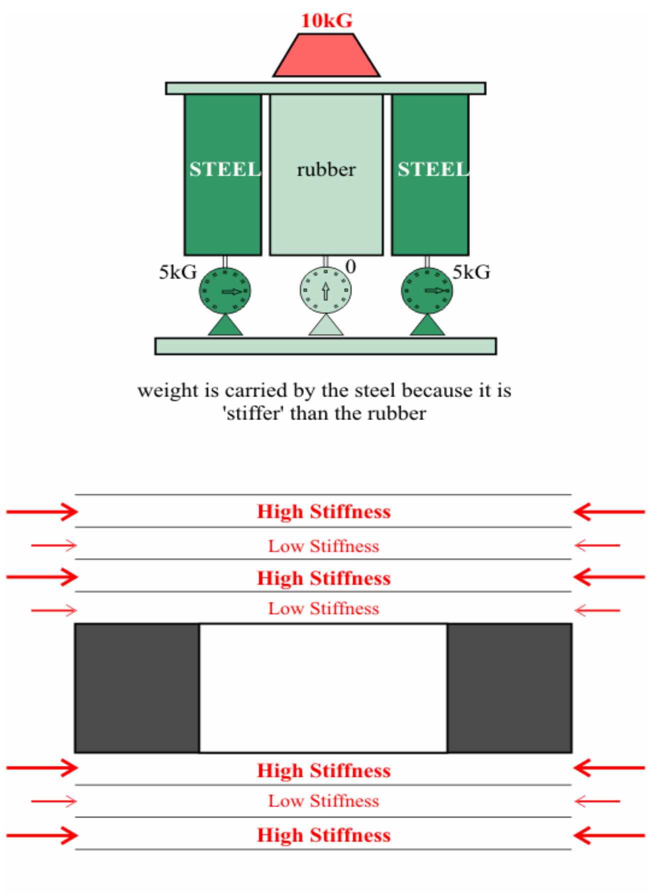


Fig 1: Variation of stresses in different layers.

To normalise (scale) the lateral stresses to a chosen rock stiffness, the 'tectonic' component of lateral stress is multiplied by the ratio of Young's Modulus of chosen and measured rock stiffness. To summarise the normalising' process:

- Choose a convenient Young's Modulus to normalise the lateral stress into.
- Subtract the gravity induced lateral stress component from the measured lateral stress to obtain the 'tectonic' portion of lateral stress.
- Multiply the 'tectonic' lateral stress with the ratio of Young's modulae (Enormalised/Emeasured).
- Add the newly calculated 'tectonic' lateral stress to the gravity induced lateral stress component.

The 'Normalising' process is summarised in the equation below:

$$\sigma_{NL}=E_N/E_M\{\sigma_{ML} - \sigma_v\nu/(1-\nu)\} + \sigma_v\,\nu/(1-\nu)$$

Where: σ_{NL} = Normalised Lateral stress
E_N/E_M = Ratio of Normalised and Measured Young's Modulae
σ_{ML} = Measured Lateral stress
σ_v = Measured Vertical stress
ν = Poisson's Ratio

Consider a hypothetical case where the overcore stress measurements were conducted at two underground sites. At a depth of 290 m a maximum compressive lateral stress of 19 MPa was measured in siltstone with elastic modulus of 24 GPa while at a depth of 400 m the maximum compressive lateral stress equal to 18 MPa was measured in sandstone with Young's Modulus of 15 GPa. The lateral stress at 290 m depth was scaled down to what it would have been if the measurement was conducted in rock with elastic modulus of 15 GPa. Calculations indicate that the normalised (scaled) maximum lateral stress at a 290 m depth is 13 MPa, 5 MPa lower than at a depth of 400 m. The higher lateral stress at 400 m depth is consistent with the increase in overburden depth.

Figure 2 below shows measured and normalised maximum lateral stresses versus the overburden depth in Australian coal mines (SCT measurements only). The overall stress distribution shows no significant differences between the measured and normalised values of stress indicating a good selection of 'average rock stiffness' chosen for normalisation. When considering single measurements at a particular mine, the normalised lateral stress values describe the true nature of the lateral stress state at a mine site. Note that many existing discontinuities in underground mines may vary the stress flow and it is sometimes possible to experience unusual stress fields at the same depth in the same mine.

Note: Typically, coal has a lower stiffness than surrounding rock and therefore the maximum lateral stress in coal is usually much lower (often less than the vertical stress). Numerous overcore stress measurements in virgin coal indicate that indeed the maximum stress is in most cases the vertical stress. The stress measurements are often influenced by pore pressure loss and gas drainage within the coal that can further reduce the measured stress magnitudes in coal strata. At this stage the normalisation process is not recommended for coal due to the complex and not well understood issues affecting the stress in coal.

INCREASE IN STRESS MAGNITUDE WITH OVERBURDEN DEPTH

Numerous stress measurements in Australia and overseas compiled on the World Stress Map (Reinecker, 2003) indicate that the vertical and also the horizontal stresses increase with overburden depth. The normalised values of maximum lateral stress measured by SCT in NSW and Queensland coal mine roofs (Figure 3) clearly indicate increase of lateral stress with depth.

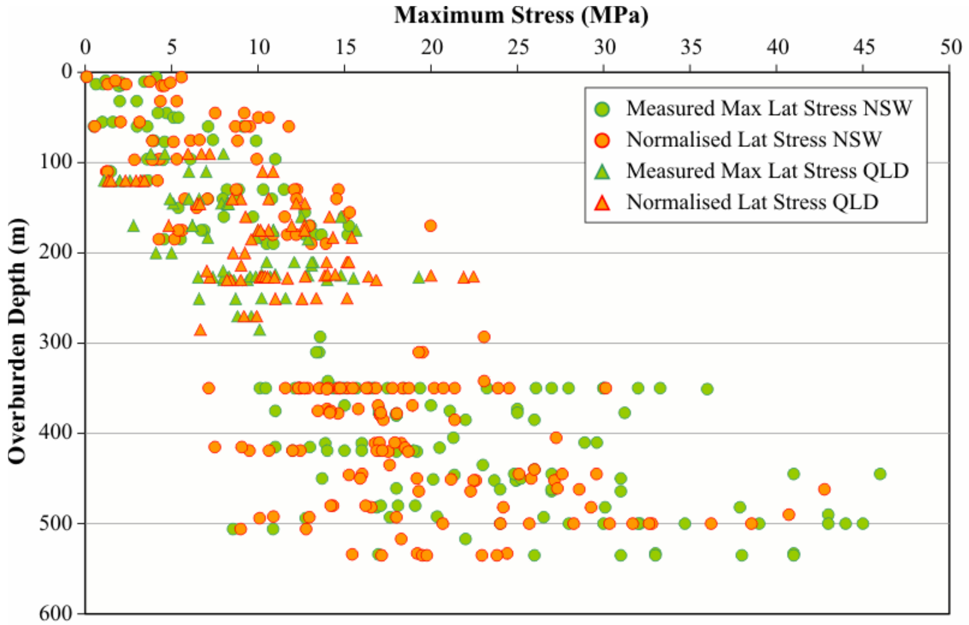


Fig 2: Measured and normalised lateral stresses versus overburden depth in Australian coal mines (SCT measurements only).

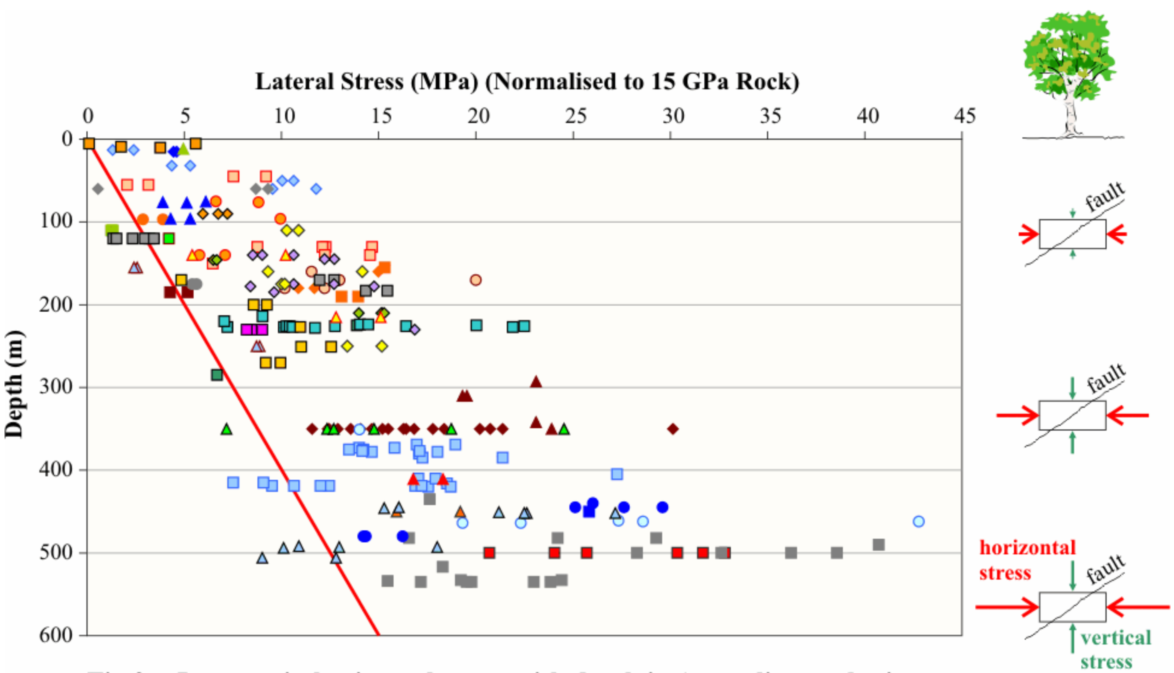


Fig 3: Increase in horizontal stress with depth in Australian coal mines as measured underground (SCT measurements only).

To explain the possible mechanisms of lateral stress increase with depth, several issues need to be considered. In response to a constant tectonic interaction within the ground, the rock mass on a large scale is literally broken (intercepted with many discontinuities such as faults, bedding planes, weathered dykes etc). When subject to loading, these large rock geometries would exhibit complex post failure behaviour. This behaviour can be compared to a triaxial test on broken rock sample where the maximum load (σ_1) that the rock sample is able to sustain without further failure increases with the confining stress (σ_3) applied to the sample. The triaxial test is described in Figure 4 below.

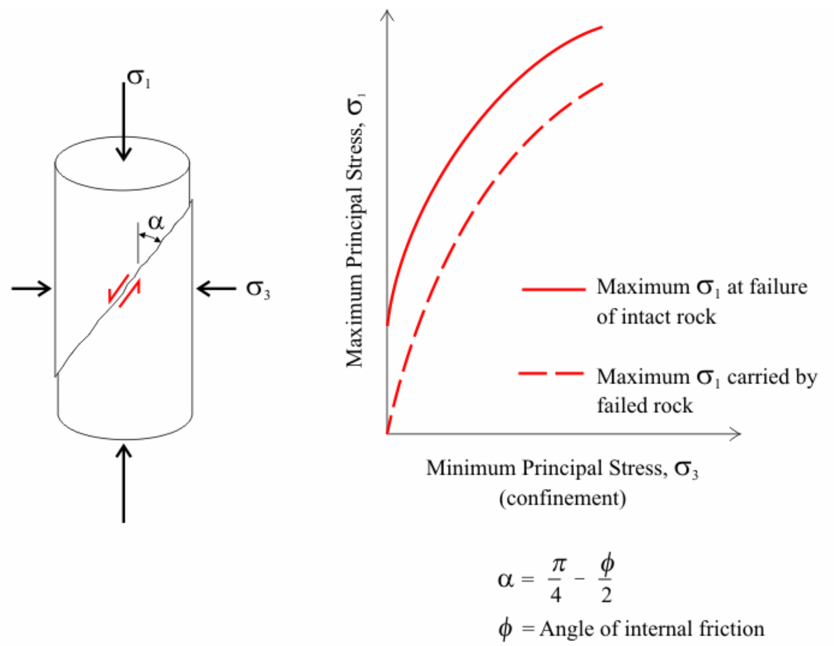


Fig 4: Increase in rock strength versus applied confinement during the triaxial rock strength test.

The exact nature of the ground behaviour may not be known, however the confining stress (σ_3) that increases with the depth of cover would provide a mechanical lock to the discontinuities within the ground rock mass. It is therefore not surprising that when laterally loaded, deeper sections of a broken rock mass would sustain larger lateral strains while near the surface where the confinement stresses are low, displacements (slips) along the discontinuities would occur more often relieving excess lateral stress until stress equilibrium is reached. The principle of this mechanism is depicted on the right hand side of Figure 3.

The stress measurement data clearly indicate that the lateral stresses measured in NSW and Queensland sedimentary strata are considerably higher than the vertical stress. These large lateral stress magnitudes and their increase with depth appear consistent with an active tectonic plate movement that would provide stress equilibrium within the ground (as discussed above).

A wide spread of lateral stress values is typically attributed to many discontinuities and non-homogeneous rock that exist within the ground. The faulted or otherwise disturbed ground can either concentrate or reduce the stress field depending on their location and depth. The probable range of lateral stress (Figure 3) versus the overburden depth can be used effectively together with geophysical logging and borehole breakout analysis (MacGregor, 2003) to estimate the probable stress at green field sites.

While substantial amount of stress measurement data has been compiled all around the world and presented in the compilation of the World Stress Map (Reinecker, 2003), SCT measurements are unique to the Bowen and Sydney Basins. The role of horizontal stress and its affect on strata behaviour in underground coal mines has been well documented (Siddall and Gale, 1992, Hebblewhite, 1997 and Mark, 2002). In most mines it can be expected that both, the vertical and the lateral stresses will increase as the mine advances to deeper ground.

NUMERICAL SIMULATION OF LATERAL STRESS IN FAULTED STRATA

Underground observations indicate that when the lateral stress exceeds the rock strength, low angle thrust faults form along the maximum shear planes. These planes are typically oriented at angles equal to $\pi/4 - \varphi/2$ from the direction of maximum compressive stress (σ_1) (Goodman, 1989). Their cross-sections appear to be parallel to the bedding planes indicating that the maximum stress initiates the fault propagation plane in rock with similar properties and strength. During the failure, an internal angle of friction (φ) in sedimentary strata would typically range between 25-35˚ indicating that a typical thrust fault in stone would dip at approximately 30˚. Any subsequent slip along the fault planes due to ongoing tectonic movement would modify the interface properties and in general, reduce the friction along the surfaces.

A number of thrust faults were modelled using the UDEC and FLAC codes to simulate the stress equilibrium that can be sustained within the faulted ground when active tectonic displacements are applied to the model boundaries. The frictional properties along the thrust faults were varied from 5˚ to 30˚ degrees while gravity was applied to the rock mass. The results shown in Figure 5 indicate that the increase in lateral stress with overburden depth in the models were similar to the increase in lateral stress measured underground. This implies that the Sydney and the Bowen Basins are currently experiencing active tectonic compression.

As expected, the modelled results indicate that the frictional properties of fault interfaces influence the magnitudes of lateral stress that the ground can sustain during fault movement. For the fault planes with very low friction (angle of friction below 5˚) the lateral stress would be approximately hydrostatic. At 15˚ the ground appears to be able to sustain lateral stress of approximately twice the vertical stress while at 30˚ the lateral stress increases to more than three times the vertical stress (depending on the depth of cover).

Both, the modelled results and the actual underground stress measurements indicate that at the surface and at a shallow depth the ground is still able to sustain a significant portion of the lateral stress (Figure 5).

Tectonic Factor

The Tectonic Factor is a useful parameter that describes the amount of lateral strain induced by tectonic forces within the ground. The regional tectonic factor can be used to estimate an average 'background' lateral stress in undisturbed virgin ground where no discontinuities or other major structures exist.

The Tectonic Factor can be calculated by dividing the 'excess tectonic lateral stress' by Young's Modulus. The calculations can be described by:

$TF= \{\sigma_1 - \sigma_v \nu/(1- \nu)\}/ E_M$

Tectonic factors calculated for all SCT virgin stress measurements in Australian mines are plotted below (Figure 6).

The results indicate that the tectonic factors increase with the overburden depth. This is consistent with the higher strain equilibrium present within the deeper ground. The lateral spread of the Tectonic Factor data is attributed to the geological discontinuities and non-homogeneous rock that exist underground.

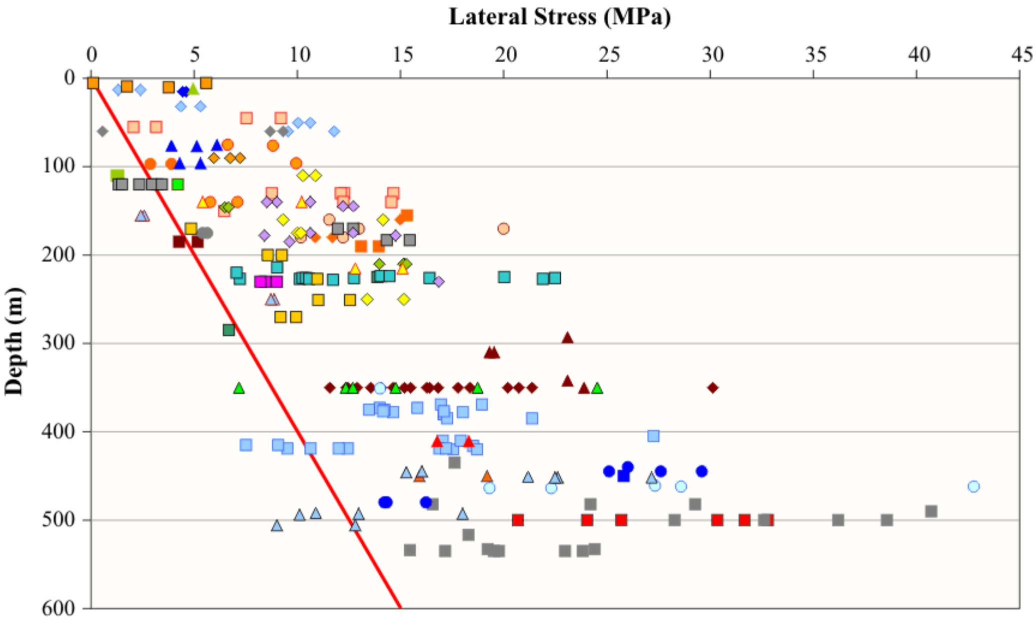
Directions of Major Horizontal Stress

Underground stress measurements indicate that lateral stress directions can vary substantially due to a large number of geological structures underground. In the Bowen Basin the directions of major lateral stress are in most cases confined to the North to North-East quadrant as shown in Figure 7. In NSW coalfields the maximum lateral stress directions can vary with the location and are best plotted on the regional map. Currently, other stress direction maps are being constructed in SCT to provide better understanding of the regional stress.

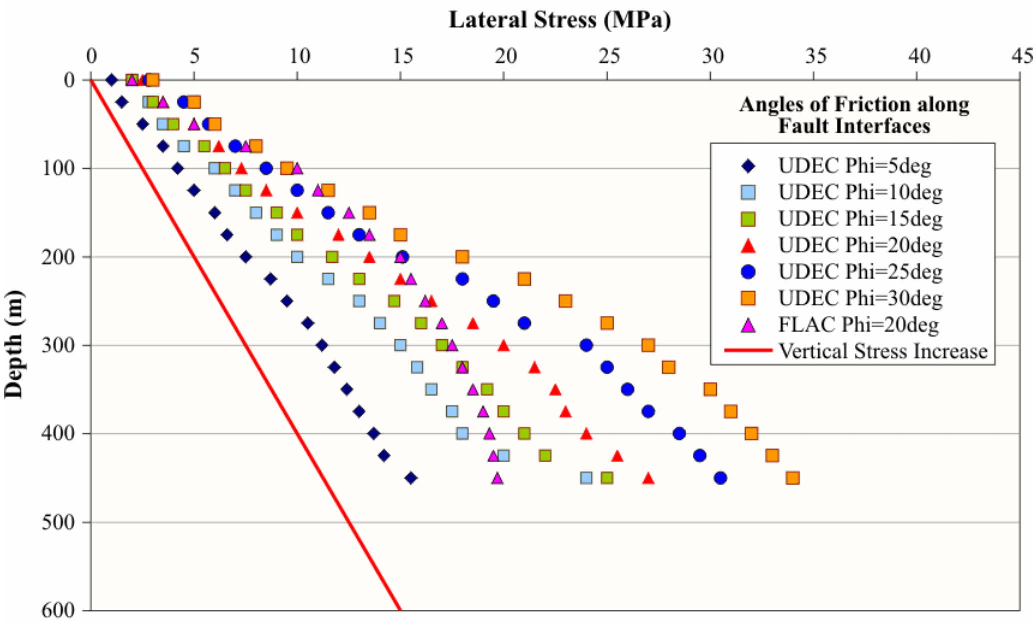
Variations in lateral stress direction that are sometimes measured in the mine are usually caused by at least two factors:

1. The *in situ* geological structures that can change directions of the stress flow in the mine.
2. If the lateral stresses are almost equal in all directions, the direction of maximum lateral stress can vary with even a slight change in stress.

The borehole breakout survey that is usually undertaken as part of the geophysical investigations during the exploration drilling is the best method to accurately determine the directions of maximum lateral stress flow in the explored area (MacGregor, 2003).



a) Maximum normalised lateral stress in rock versus depth for Australian mines (scaled to 15GPa rock).



b) Induced lateral stress in faulted ground driven by lateral displacements of modelled boundary (UDEC and FLAC).

Fig 5: Comparison of measured and modelled lateral stress in faulted ground.

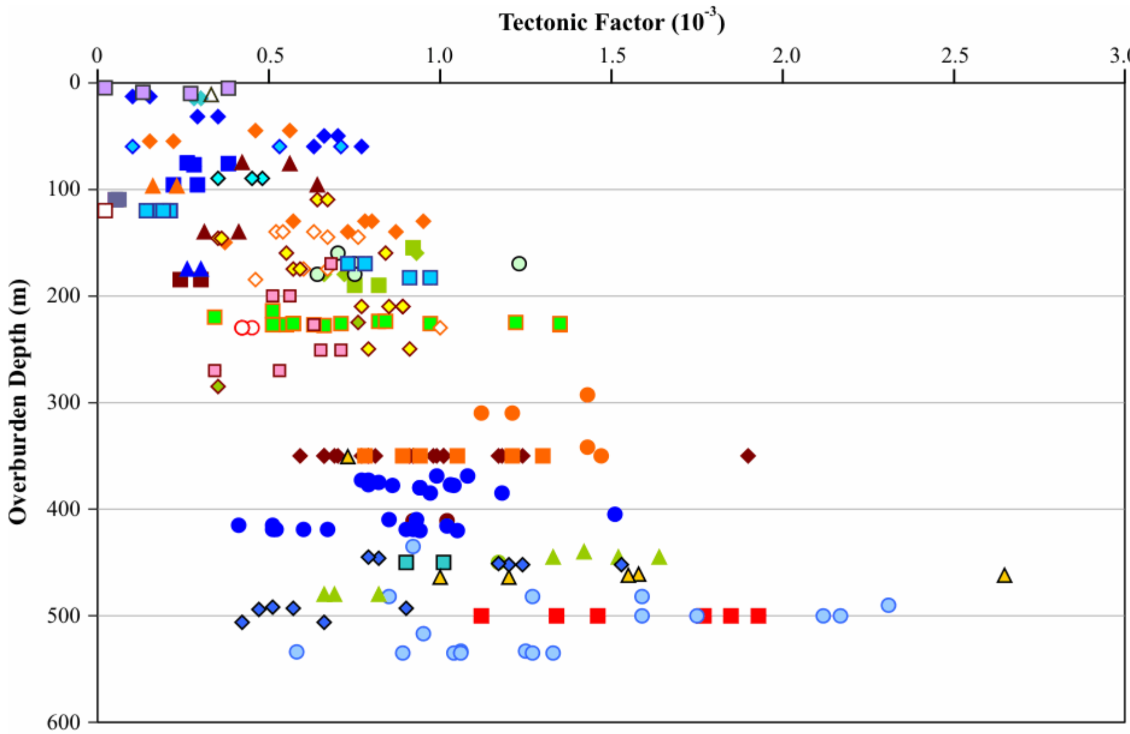


Fig 6: Calculated tectonic factors from stress measurements in Australian coal mines (SCT measurements only).

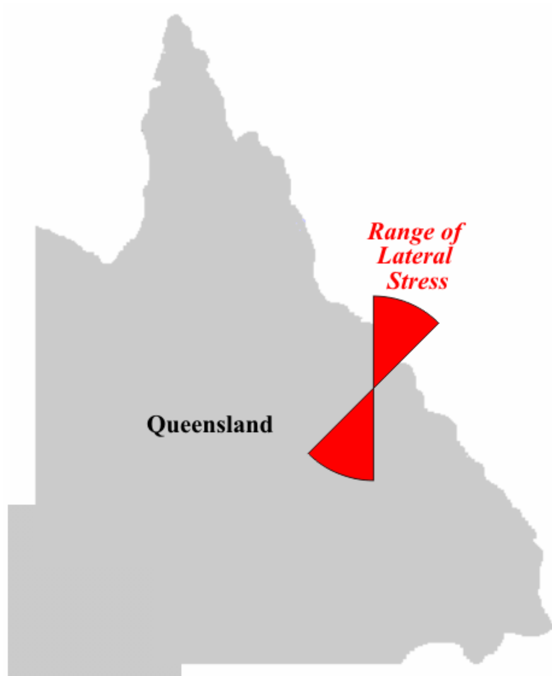


Fig 7: Range of maximum lateral stress directions as measured underground.

CONCLUSIONS

This study presents numerous *in situ* virgin stress measurements conducted by SCT. The complexity of the *in situ* ground behaviour suggests that it may be difficult to accurately predict stress levels in the mine without actual measurements, however, a preliminary stress estimation is possible using the data presented in this paper together with other nearby stress measurements and borehole surveys.

Several important points can be deduced from this study:

- The measurements clearly indicate that in most cases, the lateral stresses are considerably higher than the vertical stress.
- An increase in lateral stress with the depth of cover can be expected in the Sydney and Bowen Basins.
- Geological discontinuities and non-homogeneous sedimentary strata can significantly influence the stress directions and magnitudes in the mine.

The data presented here strengthens the understanding of stress behaviour in underground coal mines. In response to the stress range in rock of various stiffness, normalisation (stress scaling) technique was developed that allows calculations of stress in rock of any stiffness. Recognising that a large portion of the lateral stress is probably of a tectonic origin, the tectonic factor was developed to help identify areas of highly stressed ground. Construction of stress maps showing detailed lateral stress directions in selected areas is currently in progress to help with mine layout designs.

Many geotechnical methods including numerical modelling are commonly used to predict ground behaviour. These methods require a detailed knowledge of stress distribution in the ground. A reliable source of stress information is now available to provide realistic estimates of stress in underground workings and to establish correct boundary conditions in numerical models.

A number of thrust faults were modelled using the UDEC and FLAC codes to simulate stress equilibrium that can be sustained within the faulted ground when active tectonic displacements are applied to the model boundaries.
The results indicate that the increase in lateral stress with overburden depth in the models were similar to the increase in lateral stress measured underground. This study implies that the Sydney and the Bowen Basins are currently experiencing active tectonic compression.

Further research is in progress to enhance current understanding of stress and its influence on stability of underground workings in coal mines.

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